



# Realistic loss of plant species diversity decreases soil quality in a Tibetan alpine meadow

Xianhui Zhou<sup>a</sup>, Wenjuan Wu<sup>a</sup>, Kechang Niu<sup>b,\*</sup>, Guozhen Du<sup>a,\*</sup>

<sup>a</sup> State Key Laboratory of Grassland and Agro-ecosystems, School of Life Sciences, Lanzhou University, Lanzhou 730000, China

<sup>b</sup> Department of Ecology, School of Life Sciences, Nanjing University, Nanjing 210023, China



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## ABSTRACT

With rapid changes in climate conditions and grazing regimes, a decline in soil quality has become a main challenge for sustainability of Tibetan rangeland. Increasing evidence highlights the significance of plant biomass, but few studies test the role of realistic loss of plant diversity in impacting soil quality. We hypothesized that loss of species diversity will decrease soil quality, not only through lost standing biomass (i.e., “mass effect”) but also directly via the loss of the “diversity effect”. Considering the realistic loss of species diversity following overgrazing, grazing exclusion and climate change, we experimentally removed grass, sedge and various forb species from a Tibetan alpine meadow to test this hypothesis. After target plant species had been removed for five years, we examined the effect of the species removal on the plant community and soil quality with Bayesian linear mixed effect models and inferred potentially causal linkages between plants and soil with a Bayesian network. Results showed (i) overall, plant species removal not only significantly decreased plant diversity and standing biomass but also decreased soil organic matter and nutrients; (ii) the standing biomass decreased more pronouncedly in response to the removal of sedge and grass species, but plant diversity and soil nutrients decreased more pronouncedly in response to the removal of various forb species; and (iii) the loss of species diversity rather than standing biomass was directly associated with the decline in the soil quality, especially a decrease in soil available P. In short, our results indicate that realistic loss of plant species diversity can decrease soil quality in a Tibetan alpine meadow through lost the “diversity effect”. The functional significance of plant species diversity in maintaining soil quality supports the expectation of local pastoralists that diverse plants, promoted by traditionally rotational grazing, can ensure the sustainability of alpine soil and Tibetan rangeland.

## 1. Introduction

With rapid changes in climatic conditions and grazing regimes, rangeland degradation has become a main challenge worldwide, especially in Palearctic grassland (Török and Dengler, 2018). The degradation is mainly characterized by a loss of plant diversity and soil quality under improper management and overgrazing on the rangelands of Mongolia and China (Pfeiffer et al., 2018). Over thousands of years of traditional grazing (i.e., low-to-moderate rotational grazing regimes), the rangeland of the Tibetan Plateau dominated by alpine *Kobresia* species accompanying abundant grass and forb species (Niu et al., 2010; Miehe et al., 2019). The high plant diversity not only promotes ecosystem multifunctionality and services but also ensures the sustainability of the rangeland, as anticipated by local pastoralists and supported by comprehensive experimental studies (Shang et al., 2014; Mu et al., 2016; Dong et al., 2017). However, with rapid changes

in grazing regimes and climate conditions over the last four decades, the loss of plant diversity and degradation of rangeland soil has become a main challenge for sustainability of traditional husbandry (Miehe et al., 2009; Harris, 2010; Dong et al., 2011).

In general, the loss of plant diversity and change in soil quality are mainly characterized by (i) overgrazing-induced loss of plant biomass and abundance of sedge and grass species but the promotion of various forb species, in conjunction with a loss of soil organic matter and fertility (Gao et al., 2011; Mu et al., 2016; Niu et al., 2016a; Wang and Wesche, 2016; Abdalla et al., 2018) and (ii) various “rangeland improvements” (e.g., grazing exclusion, fertilizer addition and grass planting) and climate change (e.g., experimental warming and watering), which promote forage production through increased abundance of grass and/or sedge species at the expense of losing various forb species (Klein et al., 2007; Chen et al., 2013; Niu et al., 2014; Zhang et al., 2015; Shang et al., 2017). Increasing evidence shows that the loss

\* Corresponding author.

E-mail addresses: [kechangniu@nju.edu.cn](mailto:kechangniu@nju.edu.cn) (K. Niu), [guozdu@lzu.edu.cn](mailto:guozdu@lzu.edu.cn) (G. Du).

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of plant diversity is associated with the degradation of soil; however, it remains a challenge to clarify the functional role of plant species loss in changing soil quality.

Theoretically, the impact of species diversity on soil quality and function occurs simultaneously through two mechanisms, that is, “mass effect” and “diversity effect” (Diaz et al., 2007; Garnier et al., 2016). The mass effect is due to the key role of plant biomass in promoting ecosystem functioning (Wardle et al., 1999; Garnier et al., 2004). In this mechanism, plant species diversity indirectly impacts soil quality and function by promoting the production of plant community biomass (Loreau and Hector, 2001; Hooper et al., 2005). Moreover, plant species diversity can directly impact soil quality and function through the diversity effect (Grime, 1998; Garnier and Navas, 2012), also termed the “singular hypothesis,” which suggests that plant species are unique, and each contribute to soil attributes and functioning (Eisenhauer et al., 2010). For instance, diverse plant species can adequately uptake and utilize various soil resources via a diverse strategy of resource acquisition and utilization (Tilman, 1988; Bazzaz, 1996); however, diverse plant species can promote soil quality and function through facilitation among different plants and the support of diverse soil organisms (van der Heijden et al., 1998; Bardgett and Wardle, 2010).

Accordingly, in a Tibetan alpine meadow, it is possible that the loss of plant diversity can induce a decline in soil quality and function through the “mass effect” of losing plant biomass, as well as via the loss of the “diversity effect”. Numerous studies have reported a negative effect of losing biomass, but few studies have assessed the role of losing the diversity effect on changes in soil quality in Tibetan rangeland (Zheng and Cao, 2015; Wang et al., 2018). This is partly because of difficulties in distinguishing and isolating the role of realistic species loss from other effects in impacting soil quality and function. For example, nitrogen enrichment in the Tibetan meadows increases productivity but decreases the diversity of plants and microbes in conjunction with a decline in soil P availability (Liu et al., 2012; Niu et al., 2014). However, we cannot distinguish the effect of losing plant species diversity in decreasing soil available P from the depletion of soil available P caused by increased plant biomass. Thus, direct removal of different species and/or functional groups is an appropriate approach to reveal the effect of realistic loss of species diversity or functional groups on soil quality and function (Turkington and Harrower, 2016). With high plant species diversity within a plant community (> 30 species per 0.25 m<sup>2</sup> plot) and sensitive response of soil function to changes in biotic and abiotic factors (Cao et al., 2004; Niu et al., 2016b), the alpine meadows on the eastern Tibetan Plateau provide an ideal ecosystem for a plant species removal experiment.

Considering the loss of sedge and grass species due to overgrazing and of different height forb species under various “rangeland improvement” practices, we performed a set of species removal experiments over the last eight years. With this long-term experiment, we aimed to reveal the role of losing species diversity in changing soil quality and ecosystem function. We hypothesized that loss of plant diversity decreases soil quality not only through a loss of plant biomass but also via a loss of plant diversity. Specifically, we attempted to answer two questions:

- (i) Does removal of different species have a different impact on plant community diversity and biomass, as well as on soil organic matter and nutrients?
- (ii) Do differences in soil organic matter and nutrients mostly cause changes in plant diversity rather than a change in plant community biomass?

Based on the results, we attempted to discuss the relevant rangeland regimes to ensure sustainable grazing management.

## 2. Methods

### 2.1. Study site

Our study site is located at the Lanzhou University Research Station of Alpine Meadow and Wetland Ecosystems (35°58'N, 101°53'E) in Maqu County in Gansu Province, on the eastern Tibetan Plateau (Zhang et al., 2014). The altitude of the site ranges from 3485 to 3542 m, with a mean annual temperature of 1.2 °C ranging from −10 °C (in January) to 11.7 °C (in July) and with the mean annual precipitation of 620 mm, occurring mainly during the relatively warm months, based on data from the last two decades. The natural vegetation at the site belongs to typical alpine meadow, dominated by *Kobresia graminifolia* with abundant grass species, for example, *Elymus nutans* and forb species, for example, *Anemone rivularis* and *Poa poophagorum* following traditionally, low-to-moderate rotational grazing by domesticated yak and Tibetan sheep (Niu et al., 2009). Although the organic matter content is high in the top soil (0–10 cm depth), the peat layer ranges from 30 to 50 cm in thickness, with low soil nitrogen (N) and phosphorus (P) content, classified as typical alpine meadow soil (Niu et al., 2016b).

### 2.2. Species removal experiment

During the summer of 2010, we began to prepare the plant species removal experiment in a relatively flat alpine meadow within the site that was fenced in 2007. We surveyed species diversity and measured the average height for every species within 50 quadrats with a size range from 0.1 m<sup>2</sup> to 4 m<sup>2</sup>. Since livestock grazing was excluded during the growing season from March to October every year, the dominance of *Kobresia* species declined while the canopy height of the plant community increased to 30–50 cm. Due to low  $\beta$  diversity of the plant community and soil heterogeneity (Niu et al., 2016b), we set up relatively few replicates of plots for each species removal treatment to balance the considerable labor and long-term fieldwork.

In May 2011, we established 30 1.5 × 1.5 m plots for six treatments of plant species removal with five replicates for each treatment. According to the typical design of a randomized block experiment, we set up five blocks as replicates (plots) and randomly allocated six treatments to each of the six plots within every block. Considering the realistic loss of plant species diversity in response to land use and climate change as mentioned above, the six treatments are as follows: (i) non-removal (control), with 30–40 species in each 0.25-m<sup>2</sup> plot; (ii) removal of sedge species (i.e., the dominant species); although only three to four species were removed, the loss of aboveground biomass was comparable with that of the loss of 10–20 grass and forb species; (iii) removal of tall (above 30 cm) grass species, that is, removal of 10–12 productive plant species; (iv) removal of tall forb species; most of these approximately 9–14 forb species belong to inedible “weed” species often excluded in various rangeland improvement practices; (v) removal of forb species (10–16 species) with intermediate height (15–30 cm); these species often accompany sedges in plots undergoing traditional grazing but are easily lost after long-term fertilization (Niu et al., 2009); and (vi) short (below 15 cm) forb species (11–15 species) that contribute relatively little biomass but much diversity, which also can be easily lost from the local community under changing climate conditions. Since the occurrence of difference species varied across plots, the number of removed species also varied across plots. Notably, forb species were grouped into three levels according to species-specific height because height diversity is the most important trait in determining community biomass production in this alpine meadow (Liu et al., 2016). More importantly, dividing such six treatments of species removal can ensure comparable loss of species diversity and/or biomass among treatments.

From May 2011–2017, in every week of summer, we manually removed each individuals of the target species with scissors within each of the 30 1.5 × 1.5 m plots. Basically, the removal of plants was focused

on the shoot, but we also attempted to remove roots without damaging non-target neighboring individuals.

### 2.3. Measurement of plant community and soil variables

After five years of removal, from 2015 to 2017, there was regrowth of very few individuals of the target species, and we began to measure plant community over three years and soil variables in 2016. From mid-August to early September, in each of the 30 plots, we measured species diversity and harvested stems and leaves in a 50 × 50 cm quadrat after estimating the projected coverage of total plants. For every plant species within each plot, the ramet number and projected coverage was recorded and estimated to measure the abundance of every species in terms of individual number and coverage (Niu et al., 2016b). The standing biomass was weighted after shoots were dried at 80 °C for 48 h.

After the plants were harvested in each quadrat, three soil cores (2.5 cm diameter × 20 cm depth) were randomly collected and mixed completely to measure the soil quality. The soil samples were sieved through a 2-mm mesh and were air dried at the field station. The dried soil was then ground and sieved through a 0.25-mm mesh for measurements of soil pH, soil organic matter content and soil nutrients. The soil pH was measured using a 1: 2.5 ratio of air-dried soil to water (Chapman and Pratt, 1962). Soil organic matter was calculated based on the measurement of soil organic carbon using an Elemental analyzer. Soil total phosphorus and nitrogen were measured using H<sub>2</sub>SO<sub>4</sub> fusion with phosphate detection and Kjeldahl digestion, respectively. Soil available nitrogen and phosphorus concentrations (Olsen-P) were measured with the Walkley–Black method (Nelson and Sommers, 1982) and the molybdate colorimetric test after perchloric acid digestion (Sommers and Nelson, 1972).

### 2.4. Statistical analysis

For each plot in every year, we measured species diversity with the Shannon diversity, which was calculated based on species number (richness) and relative abundance of each species in terms of individuals and coverage using the R package ‘vegetarian’ (Charney and Record, 2009). Since species diversity based on individual numbers and coverage is highly correlated ( $R^2 > 0.8$ ,  $P < 0.01$ ), we used only species diversity based on individual number, which was not necessarily correlated with biomass production mathematically.

We used a Bayesian linear mixed effects model to estimate the effect of year, treatment and block on response variables (e.g., plant diversity, plant community biomass and soil variables). We employed the Bayesian method since the data were more suitable for Bayesian regression; the distributions of response variables from the control were used as prior distributions, and few available data but more parameters need to be estimated when considering the interaction between years and treatments. Moreover, we were more interested in discussing the uncertainty of treatment effects over measured time and place, which are more significant in ecology (Ellison, 2004). We used the ‘brm’ function from the R package for the Bayesian model, with prior distribution of response variables obtained from control data using the ‘get\_prior’ function (Bürkner, 2007). Since the Beta, Gamma and Gaussian model family well fit the distribution of plant coverage, biomass and soil organic matter, and species diversity and soil nutrients, respectively, we employed these distributions in corresponding brms-models. After model comparison, we used year and block as random terms since there were no significant effects of these variables. The probability distribution of effect size for every treatment (compared to the control) was estimated in an averaging model with MCMC (chains = 4).

With a user-specified path diagram, the linkage between plant diversity and soil variables is often assessed with path models, for example, Structural Equation Model (Grace, 2006). In our study, however,

we did not know the specific effect paths from plant to soil or among soil variables. We attempted to explore only potentially casual associations based on a small dataset, rather than confirm or reject existing associations. Thus, we employed the Bayesian network to conservatively infer potential direct and indirect associations using learning algorithms based on data structure and probabilistic graphical models, which is more suitable for small datasets (Koller and Friedman, 2009; Isobel et al., 2010; Hamilton et al., 2015). With learning ability, we believe that Bayesian networks are well suited to detect the complex associations between plant community variables and soil variables. Although some of our variables did not fit the Gaussian distribution very well, we used the Gaussian Bayesian Network (GBN) because (i) all variables in our study were continuous data, (ii) transformation of data did not impact conditional relationships and the GBN (Koller and Friedman, 2009), and (iii) GBN does not require any discretization of the data (Chen and Pollino, 2012). In brief, we used a random network as the prior network and carried out a Hill-Climbing learning procedure based on the AIC score; we calculated potential association and its significance as well as direction based on the partial correlation and conditional probability in the learning using the package ‘bnlearn’ (Scutari, 2010) and visualized the network with the help of the package ‘Rgraphviz’ (Hansen et al., 2018).

## 3. Results

### 3.1. Impact of the removal of different species on the plant community

Compared with the control, over three years (2015–2017), (i) plant species diversity significantly decreased with the removal of grass species and various forb species but not with the removal of dominant sedge species (Fig. 1a); (ii) standing biomass consistently and significantly decreased in all treatments of plant species removal, with more pronounced decreases due to the removal of sedge and grass species (Fig. 1b); and (iii) plant coverage tended to decrease due to the removal of grass and forb species, but not significantly in all treatments (Fig. 1c).

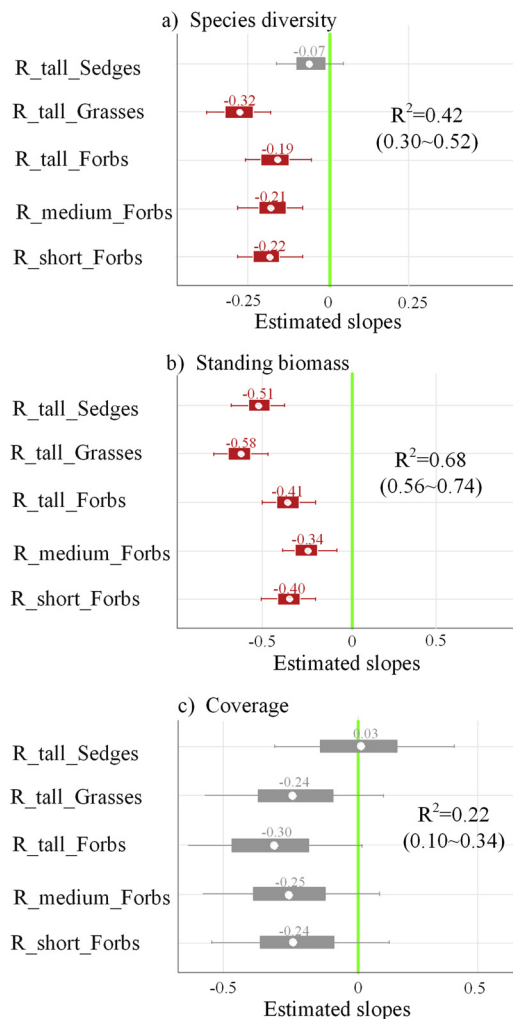
### 3.2. Impact of removal of different species on soil quality

Compared to the control, the soil organic matter content (Fig. 2a) significantly declined due to the removal of plant species in all treatments besides the removal of short forbs, with more pronounced decreases with the removal of medium-height forb species. There was no significant difference in soil pH between treatments (Fig. 2b).

Overall, compared to the control (i) soil available N increased with the removal of tall grass species (Fig. 2c), but soil total N significantly decreased due to the removal of short forb species (Fig. 2d); (ii) soil available P significantly decreased due to the removal of tall grass species and short forb species (Fig. 2e); and (iii) soil total P decreased due to the removal of tall forb species but significantly increased due to the removal of tall grass species and short forb species (Fig. 2h).

### 3.3. Linking plant community and soil quality in response to species loss

When we examined the potential linkage between plant and soil with the Bayesian network, we found plant diversity as a determinant of the whole network, rather than being a mediator of biomass impacting soil quality (Fig. 3). Specifically, loss of plant diversity was (i) directly associated with a decline in the availability of soil N and P as well as plant community biomass, although there was a positive relationship between remaining plant species diversity and soil available N determined by the biomass and soil available P; (ii) indirectly associated with a decline in soil total N and P through the loss of soil available P and N, respectively, and (iii) neither soil organic matter nor soil nutrients were significantly associated with community standing biomass and coverage but were associated with soil available N and soil pH,



**Fig. 1.** Quantifying the effect of species removal on plant community. Compared to the control, the positive (blue) or negative (red) effects of species removal on plant species diversity (a), standing biomass (b) and total coverage (c) are indicated by the estimated slope in Bayesian linear mixed effect models. The fit of the models is indicated by the median and 95% interval of  $R^2$ , and the uncertainty of the individual effects is indicated by median values (above the bars) and 95% credibility intervals, with significant effects when the 95% error bars do not overlap zero. R\_tall\_Sedges: removal of tall sedge species; R\_tall\_Grasses: removal of tall grass species; R\_tall\_Forbs: removal of tall forb species; R\_medium\_Forbs: removal of medium-height forb species; R\_short\_Forbs: removal of short forb species; for details of species removal and Bayesian regression, see the Methods section (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

respectively.

#### 4. Discussion

Under rapid change in climate conditions and land use regimes, rangeland degradation has become a main challenge for the Tibetan Plateau. The degradation has accelerated due to the interaction of the decline in soil quality and the change in plant diversity under inappropriate grazing regimes (Harris, 2010; Miede et al., 2019). Many studies have shown how soil degradation, for example, loss of soil organic matter and fertility, have an impact on the production of plant biomass and the dynamics of plant diversity. However, relatively few studies have examined how a realistic loss of plant biodiversity contributes to soil degradation, which is, indeed, difficult to distinguish from changing soil attributes following shifts in environmental regimes.

Here, based on a long-term field experiment of plant species removal, we revealed that a loss of plant diversity can induce a decline in soil organic matter and soil nutrients, especially the availability of soil P. Moreover, we showed that these decreases in soil quality were mostly induced by a loss of species diversity rather than a loss of plant biomass. Although we still need to fully reveal the underlying mechanisms, it is important to discuss the potential mechanisms with respect to biodiversity and ecosystem function. More importantly, these results are directly relevant to the impact of the loss of plant diversity following changes in grazing regimes and various projects of rangeland improvement. Hence, it is meaningful to discuss the implication of our study on grazing management and rangeland sustainability.

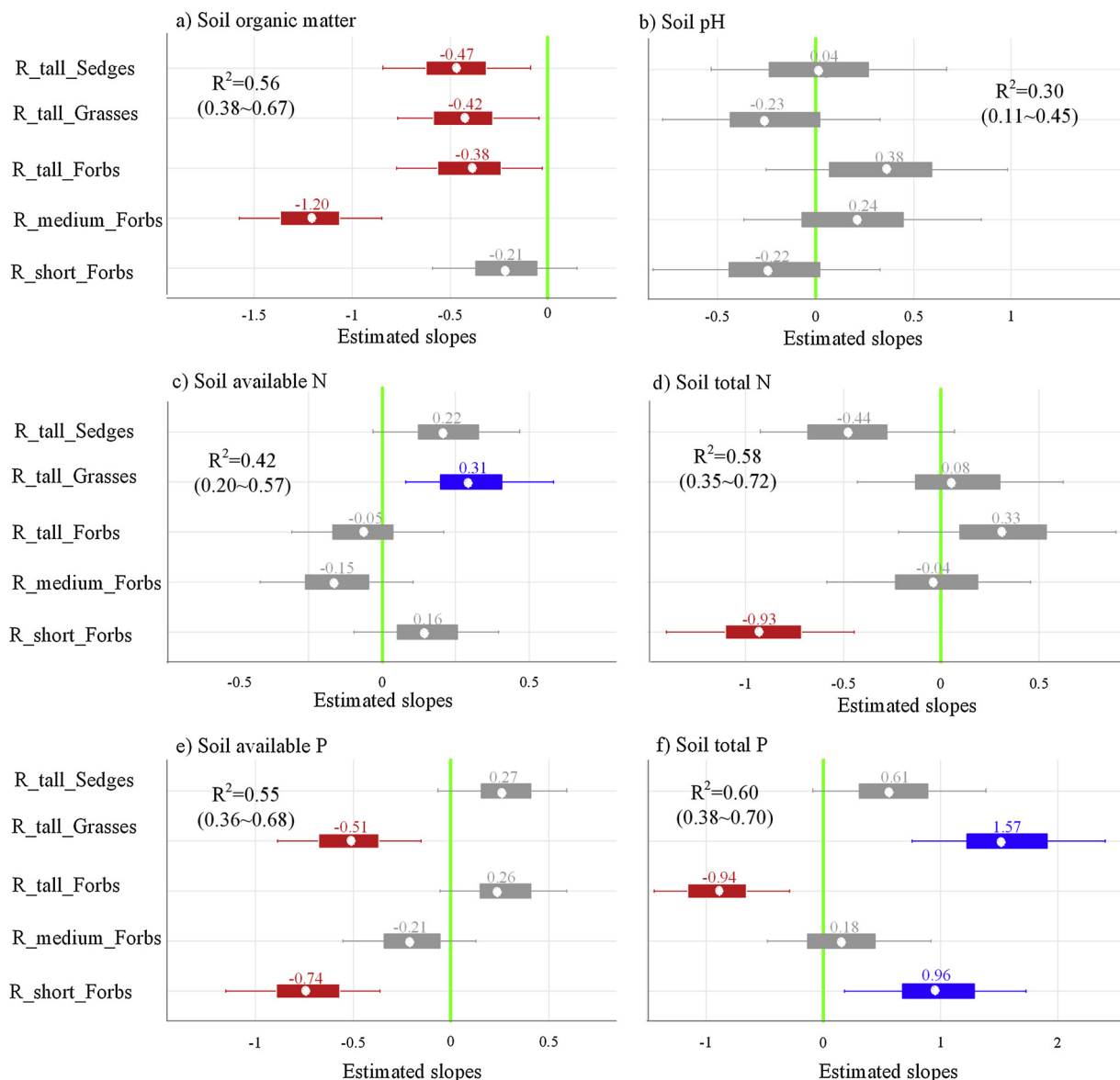
##### 4.1. Potential cause for the decline in soil quality following a loss of plant diversity

The impact of plant diversity loss on soil quality is mainly through the mass effect and diversity effect in theory (Bardgett and Wardle, 2010). The decline in soil quality induced by a loss of plant biomass possibly involves various positive relationships among plants, soil attributes and soil organisms (van der Heijden et al., 2008; Nielsen et al., 2015). For instance, a loss of plant biomass may result in a decrease in abundance and diversity of soil fauna and microbes simply due to a decline in food resources and a further decrease in litter decomposition, soil organic matter and soil nutrients (van der Heijden et al., 2008). It is likely that the effect of the loss of biomass on soil function is mediated by other factors, for example, an increase in soil temperature (Nielsen et al., 2015). Hence, the effect of standing biomass on soil organic matter and nutrients may also be mediated by various biotic and abiotic factors (Delgado-Baquerizo et al., 2017). This may explain why we did not detect a direct linkage between standing biomass and soil quality when we isolated the biomass impact from the effect of plant diversity on soil quality, as was recently addressed by Delgado-Baquerizo et al. (2017). Additionally, it is also possible that the plant biomass effect can be mediated by plant diversity because a high plant biomass can in turn promote high plant species diversity in the natural community, especially under harsh environmental regimes (Cardinale et al., 2000; Balvanera et al., 2006). Thus, we have no robust evidence against the role of the ‘mass effect’ in decreasing soil quality following species removal, although we did not detect strong direct associations between standing biomass and the decline in soil quality. This suggests that we need more detailed measurements of soil attributes to understand the role of standing biomass in impacting soil quality and function (Delgado-Baquerizo et al., 2017).

Many literature articles report that an increase in plant diversity can promote soil function and fertility (Fornara and Tilman, 2008; De Deyn et al., 2010; Cong et al., 2015). Here, we highlighted that a loss of species diversity was “directly” associated with a loss of soil nutrients, especially soil available P. The underlying mechanisms may involve a complex balance between nutrient uptake and release under the interaction of plants and soil microbes. Indeed, at the beginning of the experiment, we expected that soil nutrients will increase following plant species removal due to a decrease in nutrient uptake by the remaining plants comprising few individuals and low diversity. However, this expectation was supported by an increase in soil available N only following the removal of grass species, which indicates grasses consume high amounts of N, as documented in many early studies (Grime, 2001; Fornara and Tilman, 2008). Contrastingly, we found both soil available P and total P decreased after the removal of grass or forb species, which indicates a decrease in the release of soil P following the loss of these species. Therefore, the released soil P in the presence of these forb and grass species may offset or even surpass their consumption.

Increasing evidence shows that diverse plants can promote the abundance and diversity of soil fauna and microbes due to the unique contribution of every plant species to soil processes (van der Heijden et al., 2008; Eisenhauer et al., 2010). This plant diversity effect is more





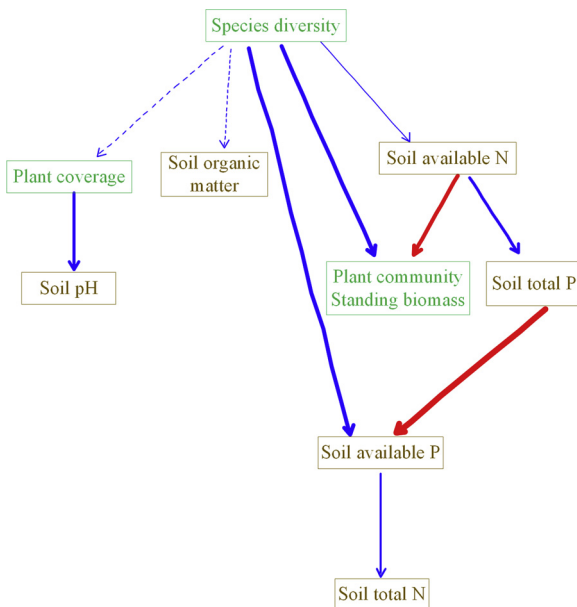
**Fig. 2.** Quantifying the effect of species removal on soil quality. Compared to the control, the positive (blue) or negative (red) effects of species removal on soil organic matter (a), soil pH (b), soil N (c and d) and P (e and f) are indicated by the estimated slope in Bayesian linear mixed effect models. The fit of the models is indicated by the median and 95% interval of  $R^2$ , and the uncertainty of the individual effects is indicated by median values (above the bars) and 95% credibility intervals, with significant effects when the 95% error bars do not overlap zero. The abbreviations for treatments of plant species removal are as in Fig. 1, with details in the Methods section (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

significant in the diversity assembly of soil arbuscular mycorrhizal fungi (De Deyn et al., 2011), which, in turn, involves the transformation of inorganic P to available P for plants, especially in soil P-limited ecosystems (Lambers et al., 2010; Laliberté et al., 2015). In our results, no significant change in soil nutrients occurred following the removal of sedge species and forb species with moderate height, suggesting a self-sufficient mechanism of soil nutrient acquisition and release among these common species. Several studies have shown that the existence of sedge species can promote carbon sequestration (Mou et al., 2018) and the release of soil available P, possibly with the help of accompanying AMF (Laliberté et al., 2015; Li et al., 2015). Additionally, it is possible that the decline in soil available P following the loss of forb plants is due to increases in the abundance of grass and/or sedge plants if these graminoid plants use more soil P than forb plants. In summary, when we focus on relevant studies on diverse plants associated with diverse microbes that promote soil nutrients (Delgado-Baquerizo et al., 2017), we are not that surprised by the decrease in soil P with the loss of plant

diversity. However, we still need to explore the detailed mechanisms of unseen processes belowground in the Tibetan alpine meadows.

#### 4.2. Implication of grazing management in Tibetan rangeland

The functional significance of the biodiversity effect in supporting ecosystem multifunctionality and services has been well addressed in the ecological literature (Naeem et al., 2002; Hooper et al., 2005). However, the potential risk of plant diversity loss with respect to rangeland sustainability is underestimated in rangeland science and by policy-makers. This is not only due to the difficulty in clarifying the impact of plant diversity loss on rangeland function but also is possibly because the “highest” priority is placed on promoting forage production in rangeland management (Weigelt et al., 2009; Wang et al., 2018). Here, we revealed that the loss of plant species diversity can induce a decline in soil quality through a loss of diversity with respect to promoting soil nutrients. We found that the highest biomass production



**Fig. 3.** The linkage between plant community and soil quality assessed by the Bayesian Network. Significant positive and negative associations between any two variables are indicated by blue and red solid lines, respectively; the line width indicates the strength (coefficients) of the partial correlation, and the direction of the arrow indicates *probable* ( $P > 0.8$ ) casual relations from one variable to another learning from data structure. Marginally significant ( $0.05 < P < 0.1$ ) linkages are indicated by broken lines. Notably, the direction of the arrow in the network does not necessarily represent causality, but since the change in plant diversity is mostly due to species removal, the arrows from plant diversity to soil quality can be used to indicate causal relationships (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

and stability of the biomass over time occurred in plots with the highest diversity rather than in plots with productive grass or sedge species (not shown), as predicted from the theory of biodiversity-ecosystem functioning (Balvanera et al., 2006; Isbell et al., 2009; Wang and Loreau, 2016). These evidence suggest that to ensure sustainability of Tibetan rangeland, the “highest” priority should be shifted to promote plant diversity, which not only promotes biomass production but also maintains soil quality over the long term (Weigelt et al., 2009).

Indeed, long-term grazing worldwide and theoretical studies make it clear that low-to-moderate grazing can ensure biodiversity and ecosystem multifunctionality (McNaughton, 1985; Glindemann et al., 2009; Briske et al., 2011). A recent review documented that low-to-moderate grazing increases soil quality (Abdalla et al., 2018). Local pastoralists in Tibetan rangeland have learned numerous lessons from over thousands of years of grazing practice, where traditionally, (low-to-moderate) rotational grazing acts as the best grazing regime to maintain the sustainability of the rangeland (Miehe et al., 2019) through promoting the diversity of plants, insects and soil micro-organisms (Mu et al., 2016; Dong et al., 2017). Under traditional rotational grazing, dominant sedge species, rather than grasses, are the main forage for domestic yaks and Tibetan sheep (Miehe et al., 2019). We showed that removal of sedge species did not change species diversity or significantly impact soil nutrients, supporting the expectation of local pastoralists that traditional grazing did not markedly change plant diversity and soil nutrients because this grazing regime mostly removes the aboveground parts of sedge plants. Moreover, sedge plants have rapid regrowth with asexual reproduction and tiller growth after grazing (Li et al., 2011), which can partly compensate for the loss of biomass during the rotation period. In contrast, although grazing exclusion, nitrogen addition and grass planting can promote the production of plant biomass in the short term, the loss of forb plants in

“improved rangeland” is likely associated with a decrease in soil quality as shown in our experiment. Additionally, when forb species are removed from plots, the remaining biomass of graminoid plants is very sensitive to climate change (not shown). Furthermore, the addition of fertilizer enhances the negative effect of species diversity loss on soil function through a rapid decrease of biodiversity of plants and micro-organisms, as well as a direct acceleration of soil acidification (Liu et al., 2012; Niu et al., 2014). We have no robust evidence to support various projects to ambitiously “improve” Tibetan rangeland, but we have learned many lessons from the effect of diversity loss on soil quality and function. In this sense, we added more evidence to the expectation of old traditional knowledge from new science, that is, ensuring Tibetan rangeland sustainability by promoting biodiversity, possibly with traditional grazing regimes.

## 5. Conclusions

Under the interaction of improper management regimes and climatic change, soil degradation and biodiversity loss have become key challenges for the sustainability of rangeland worldwide (Török and Dengler, 2018), especially the Tibetan rangeland. A large number of studies reported how soil quality and biodiversity respond to shifts in environmental regimes and the impact on the delivery of ecosystem services. Here, we experimentally revealed how a loss of different plant species influences soil quality, provided a novel explanation for the cause of soil degradation under the loss of plant diversity subjective to overgrazing, climate change and grass planting. Although we still need to fully understand the feedbacks between plant diversity and soil function, our results clearly showed that soil organic matter consistently decreased due to a loss of plant diversity, and soil P also declined following the loss of forb plants. Considering the critical role of soil organic matter and soil available P in ecosystem functioning, our results suggest that promoting biodiversity, rather than improving biomass production, is a sustainable management option for Tibetan rangeland, or even for grasslands worldwide.

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